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A NOTE ON THE VERTICAL STRUCTURE OF A TYPHOON

R. W. JAMES
70 Findhorn Place, Edinburgh 9, Scotland

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INTRODUCTION

Discussion of the vertical structure of tropical cyclones usually takes the form of a presentation of a cross section through a disturbance. Until quite recently the relevant data were not available, and cross sections published more than 2 or 3 years ago may be taken to represent merely the fantasies of individual writers. However, Simpson [1] had at his disposal sufficient aerological material to draw a cross section through a hurricane which passed over Tampa, Fla., October 7–8, 1946. Subsequent cross sections have been published by Palmén [2] and Arakawa [3], who presents an analysis of the typhoon, *Kitty*, which passed over Tokyo on August 31, 1949.

The cross-section type of presentation provides a graphic picture of hurricane structure, but for some purposes it might be considered preferable to use a parametric form of presentation, such as has been discussed by the present writer (unpublished). In essence what is studied is the total pressure drop (intensity) to the center of the disturbance at a given height, this being a measure of the mean pressure gradient within a vortex of specified horizontal scale. The vertical structure is defined by the way in which the intensity changes with height.

An alternative approach is to examine the vertical structure of the central contour anomaly, or difference in contour height of a given pressure surface between the center and the periphery of the vortex. The contour anomaly is, of course, proportional to the pressure drop divided by the density at the relevant level, so that both modes of presentation are equivalent. Which parameter we select is largely dependent on whether the raw aerological material quotes contour heights or pressure at fixed levels.

The parametric approach has been employed (James [4]) to determine the structure of a hurricane which passed over Tampa, Fla., on October 19, 1944 (Simpson [5]). The vertical structure of this disturbance was found to be quite simple; the intensity decreased with height up to about 3 km. The decay was approximately exponential. Above 3 km. an exponential decay was observed, with a more rapid decay rate. The decay in the lowest range was such that the central contour anomaly remained almost constant with height, that is to say, the lowest 3 km. of the vortex was *barotropic* in structure.

Arakawa [3] has published a number of aerological ascents taken at Tokyo during the passage of *Kitty*. We propose here to use this material to investigate the structure of *Kitty*, and to compare it with that for the Tampa hurricane of October 19, 1944.

THE PRESSURE DROP

The radiosonde ascents taken at Tokyo on August 30, 1230 hr. (local time) and on September 1, 1100 hr. may be taken to refer to the periphery of the typhoon in front and rear respectively. The mean of these two soundings has been taken as a typical periphery ascent. The ascent at 1849 hr. on August 31 was made just in advance of the eye passage, and may be taken as typical of the center of the disturbance. The pressure difference between periphery and center (intensity), plotted on a logarithmic scale against height, is shown in figure 1.

It will be noted that log intensity decreases approximately linearly with height up to about 9 km., the decay being given by

$$h=h_o \exp(-z/9.5)$$

where z is the height expressed in km., h is the pressure drop from periphery to center at height z, and h_o is the surface pressure drop. Above 9 km. the decay is more rapid, approximately as $\exp(-z/4.3)$. Above 12 km. the scatter becomes pronounced. We cannot be sure of the

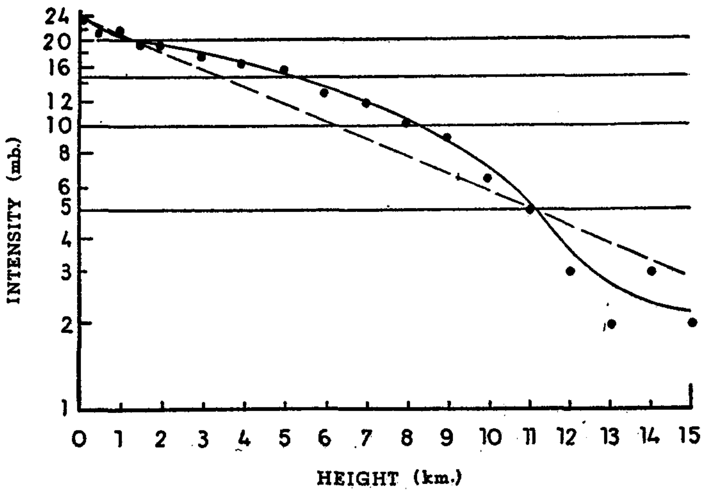

FIGURE 1.—Intensity (logarithmic scale) as a function of height in the typhoon *Kitty*.

accuracy of the ascents at these high levels, where it will be observed, the pressure drop, known only to the nearest millibar, is of the order 2–3 mb. only.

In the Tampa hurricane of October 19, 1944, the writer found an exponential decay as $\exp(-z/9.5)$ up to 3 km., and a decay as $\exp(-z/4.2)$ above that level.

In both cyclones two characteristic and almost identical decay rates are in evidence. The Lows differ in that the slow decay rate holds in the Tampa hurricane up to 3 km. only, whereas in *Kitty* this rate applies up to about 9 km.

It requires analysis of further hurricanes to establish whether this exponential decay at two characteristic rates is a general structural property, but an analysis of mean hurricane soundings published by Schacht [6] suggests that it is.

It would seem then that the vertical structure of hurricanes can be specified by two characteristic decay rates, together with the transition height from one to the other. The vertical structure may, however, be specified more crudely by fitting a single decay curve throughout the range. As a parameter we used the equivalent height, Z (James [7]), defined by

$$h_o Z = \int_0^\infty h \, dz.$$

The vortex with the one decay rate

$$h = h_o \exp(-z/Z),$$

with the same equivalent height as the actual vortex is termed the *equivalent vortex*. It is indicated by the dashed line in figure 1. It will be seen that the equivalent vortex gives a very approximate fit to the vertical profile of intensity, but that the fit with two decay rates is emphatically better

The equivalent height of *Kitty* is 7.1 km. That found

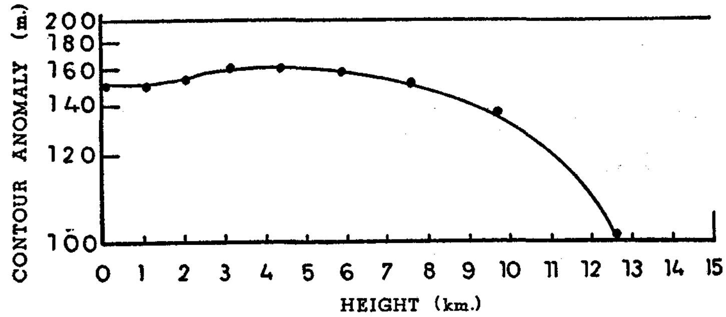

FIGURE 2.—Contour anomaly (logarithmic scale) as a function of height in the typhoon *Kitty*.

for the Tampa hurricane was 5.5 km., reflecting the shallower nature of this disturbance.

THE CONTOUR ANOMALY

The equivalence of the contour anomaly and the pressure drop or intensity for specifying vertical structure was mentioned in the introduction, and examination of structure by means of the contour anomaly introduces an important new feature.

Figure 2 shows the difference in contour height between the periphery and the center of *Kitty* for a number of pressure surfaces. The change in contour anomaly with height amounts only to a few percent in the first 8 km. At higher levels the anomaly drops rapidly.

The layer with nearly constant contour anomaly corresponds to the range in which the intensity falls off as $\exp(-z/9.5)$, while the region of decreasing contour anomaly corresponds to the more rapid decay of h.

The conspicuous structural feature of *Kitty* revealed by a study of the contour anomaly is that the vortex is nearly *barotropic* in the lowest range. It was found (James [4]) that the Tampa hurricane was barotropic, but in a more restricted range, up to 3 km. Lower level barotropy was also found in Schacht's mean hurricane soundings. It may, therefore, be regarded as a structural property of hurricanes, although the depth of the barotropic layer varies in different disturbances.

In a barotropic vortex no work can be done by taking an air-parcel around a closed circuit, for

$$\oint \frac{dp}{\rho} \equiv 0. \qquad (1)$$

Arakawa [3] has shown the barotropic nature of *Kitty* in the lower layers by evaluating the integral (1) for various circuits. The solenoidal field only becomes appreciable above 400 mb.

It is possible for a vortex to show over-all barotropy and yet still have an intense concentration of solenoids, acting in different senses in different parts of the field. This is not found to be the case with *Kitty*; her contour gradient is approximately constant with height in different parts of the field.

THE WIND FIELD

In a steady-state vortex we should anticipate a one to one correspondence between contour gradient and wind speed. In a *geostrophic* vortex the wind speed is proportional to the contour gradient. If we neglect the Coriolis parameter altogether, and consider a *centrifugal* vortex, the velocity squared over the radius of curvature of path is proportional to the contour gradient. In a hurricane we should expect an intermediate law of variation of wind with contour gradient. However, whatever the relation connecting wind and gradient, if the mean contour gradient is invariant with height, so also will be the wind speed.

The wind profiles of *Kitty* do not exhibit this constancy with height in the barotropic layer. The broadly characteristic wind profile is of a decrease of wind up to 2–4 km., with a subsequent increase. Thus, for example, at 1220 hr. on August 31, there was a maximum speed at 0.9 km. (090° 18 m/sec), a minimum at 3.4 km. (180° 2.8 m/sec), and another maximum at 5.4 km. (126° 17 m/sec). The typhoon shows no direct correspondence between wind and contour gradient profiles.

It may be remarked that a typhoon is not a steady-state system in which a one to one correspondence between wind and pressure fields may be expected. This, however, does not entirely solve the puzzle. Neglected terms in the equations of motion may be of vital importance. Durst and Sutcliffe [8] have pointed to the importance of the vertical velocity term, $w\partial v/\partial z$, in the equation of motion in the determination of the horizontal wind field in a tropical cyclone. It may be possible to conceive of a pattern of ascent which could determine the wind field irrespective of the pressure gradient. It might appear, therefore, that the dynamics of hurricanes presents highly complex problems for which there is no solution immediately in sight.

CONCLUSIONS

Whatever the theoretical uncertainties a broad morphological pattern for tropical Lows is becoming increasingly manifest.

In its lowest layers a hurricane appears to be almost barotropic in structure, the depth of the barotropic layer varying, perhaps, between 3 km. and 9 km. or more. Above this layer is a region in which pressure and contour gradients decay exponentially with height, at a rate which appears to be characteristic for a number of disturbances.

It is of interest to note that Goldie [9] and James [4] both find a constant momentum layer characteristic of occluded extratropical Lows (as of warm Highs), the limiting height being of the order 8–9 km. Exponential decay is found to be characteristic above the equimomental layer, with decay rates close to that found in our two tropical Lows. There thus appears to be a similarity in the vertical structure of tropical and mature extratropical disturbances.

No information is available touching the question of an evolutionary change in the vertical structure of hurricanes.

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